12th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference and 14th AIAA/ISSM
17 - 19 September 2012, Indianapolis, Indiana
AIAA 2012-5640

Arrival Delay Absorption Using Extended Metering with Speed Control

Tasos Nikoleris*, Gano B. Chatterji†
University of California at Santa Cruz, Moffett Field, CA, 94035-1000

Noam Almog‡
Aerospace Computing, Inc., Moffett Field, CA, 94035-1000

and

Kee Palopo§
NASA Ames Research Center, Moffett Field, CA, 94035-1000

It is often the case that due to demand-capacity imbalance at an airport, flights are assigned by air traffic controllers an amount of delay that they must absorb before their expected arrival at the airport. This paper investigates the distance needed by aircraft to absorb such delays through a speed reduction of up to 10% with respect to their nominal speed. Thirty five representative days of operations with distinct traffic volume and delay characteristics are considered for the analysis. For each day, a simulation of traffic in the NAS is conducted in the absence of any constraints on sector or airport capacity thereby resulting in delay-free aircraft landing times. Flights are assigned delays due to demand-capacity imbalances at forty major US airports, which are computed through a first-come-first-served scheduler. Distances from the airport where flights should reduce speed in order to absorb their assigned delay are computed through an aircraft trajectory generator. Analysis focuses on jet aircraft reaching their top-of-climb point at least 250 nautical miles from their destination airport. Out of all aircraft assigned delays, on average 73% were able to absorb that delay entirely through speed control. Of these aircraft, on average 93.5% of flights were able to absorb their assigned delay by reducing speed in either the same or an adjacent Air Route Traffic Control Center (ARTCC) from their arrival airport. ARTCCs that issue the highest number of advisories for speed reduction are Washington (ZDC), Atlanta (ZTL), and Chicago (ZAU). Finally, results are also provided for the specific cases of Las Vegas (LAS) and Phoenix (PHX) airports.

Nomenclature

a	=	speed of sound, m/s
D	=	drag, N
h	=	altitude, m
M	=	Mach number, dimensionless
m	=	aircraft mass, kg
s	=	ground path distance, m
T	=	engine thrust, N
V	=	true airspeed, m/s
V_{CAS}	=	calibrated airspeed, knots
γ	=	airmass-relative flight path angle, degrees

* Associate Research Scientist, University Affiliated Research Center, Mail Stop 210-8, AIAA Member.
† Scientist, University of California Santa Cruz, Mail Stop 210-8, AIAA Associate Fellow.
‡ Programmer Analyst, University Affiliated Research Center, Mail Stop 210-10.
§ Aerospace Engineer, Aviation Systems Division, Mail Stop 210-15.

I. Introduction

Arrival scheduling, or time-based metering, is an integral part of the FAA's Next Generation Air Transportation System (NextGen). At present, metering to congested Terminal Radar Control (TRACON) areas around busy airports is facilitated by the Traffic Management Advisor (TMA),[1] an air traffic controller decision support tool developed by NASA and the FAA. TMA has been designed to manage air traffic within the boundary of an Air Route Traffic Control Center (ARTCC), or simply 'Center', and it has been installed in all twenty ARTCCs of the US. Certain limitations exist, however, when extending arrival metering across ARTCC boundaries.[2] A typical example is scheduling of departures into an overhead arrival stream of a Traffic Management Advisor (TMA) metered airport located in an adjacent Center. To address these limitations, FAA is currently planning an enhancement to the TMA program that will enable capabilities for extended metering, well outside of any arrival area boundary for which the current version of TMA is designed to operate.[3] These are Adjacent Center Metering and Coupled Scheduling. Adjacent Center Metering is an extension of TMA that provides time-based metering capability to neighboring Centers.[3] Coupled Scheduling adds additional meter-points and allows the linking of time-based flow management systems. This results in more optimal balancing and distribution of delays over a greater distance from the airport or meter point.[3] Through extended metering, aircraft can absorb delays by reducing cruise speed at a long distance away from their destination airport and by meeting scheduled times of arrival at several waypoints along their route. Thus, delay absorption techniques such as path-stretching or holding patterns, which can absorb delays closer to the airport but impose additional workload to air traffic controllers, are avoided. The range required to implement extended metering with speed control depends upon the magnitude of delays to be absorbed as well as the cruise speed and altitude of aircraft bound to the airport under consideration. Moreover, each ARTCC has its own unique airspace topology, and it is expected that the usefulness of extended metering is not uniform between different Centers.

Previous research on extended metering led to the development of the Multi-Center Traffic Management Advisor (Mc-TMA) by NASA, which is an extension of TMA to adjacent Centers. References 4 and 5 outline the design of McTMA's software as well as the architecture of its scheduling algorithm. While Refs. (4)-(5) describe how delays are distributed across adjacent Centers, they do not examine the distance needed to implement extended meteringwith speed control. In light of FAA's planned deployment of Time-Based Flow Management,[3] recent research developed a concept of operations that allows airlines to adjust the cruise speed of airplanes during the en-route phase of flight to meet a predetermined in-trail spacing prior to entry into the terminal domain.[6] Moreover, cruising at reduced speed is shown to yield delay savings when a Ground Delay Program (GDP) is active, especially when GDP is terminated earlier than initially planned.[7] This research aims to provide insight into how far upstream from their destination airport aircraft need to reduce speed in order to absorb delays entirely through speed control, under current operations in the National Airspace System (NAS).

Three research questions will be the main focus of this paper. First, how many Centers upstream does an aircraft need to reduce speed in order to absorb delay due to congestion in the terminal airspace? Second, which Centers must issue the most advisories for speed reduction if delays were to be absorbed through speed control? Controllers handling traffic in these Centers might experience an increase in workload due to advisory issuance. Third, what is the amount of delay that cannot be absorbed in the airborne phase through speed control? This delay needs to be absorbed elsewhere and, therefore, it can be pushed back to the ground or absorbed through a path stretch maneuver. To address these questions, thirty five representative days of operations with distinct traffic volume and delay characteristics are considered for the analysis. For each day a high-fidelity simulation of the NAS is performed in order to generate delay-free aircraft arrival times at forty busy US airports. Arrival delays at these airports are estimated by modeling the airport as a single server queueing system and using hourly Airport Acceptance Rates as server capacities. An aircraft trajectory generator then estimates the distance from the destination airport where each aircraft must reduce speed to absorb its prescribed delay. It is important to note that this approach does not emulate FAA's planned implementation of the extended metering capability, which is based on nonlinear segmentation of the delay-absorption problem between several metering points along an arrival flow. Also in this research, aircraft are assumed to meet their assigned STAs precisely. Therefore, the analysis does not take into account stochastic trajectory conformance errors. Despite the simplification in generating aircraft STAs and the assumed deterministic environment, this paper provides insights into the magnitude of the extended metering problem by estimating distances required to absorb delays caused by demand-capacity imbalances at busy airports under current levels of traffic in the NAS. Moreover, the analysis identifies airports where implementation of extended metering exhibits the largest potential for absorbing flight delays entirely through speed control. Two such airports, namely Phoenix Sky Harbor International Airport (PHX) and McCarran International Airport in Las Vegas (LAS), are also candidate locations for a major NASA project, the Air traffic management Technology Demonstration-1 (ATD-1) field test,[8] and they are examined in more detail.

The rest of the paper is organized as follows. Section II provides background on the three main computational tools used in this research. The method for estimating delays and an anlytical formulation to calculate the distance required to absorb them is described in Section III. Analysis results are presented and discussed in Section IV. Finally, Section V summarizes the main conclusions of this study.

II. Background on Computational Tools

This section provides a summary of the three principal computational tools employed for generating the results of this study. The first is the Airspace Concept Evaluation System (ACES), an air traffic simulation tool. A brief description of ACES is provided in Section II.A. The second is the First-Come-First-Served (FCFS) scheduler described in Section II.B. Finally, Section II.C describes the procedure followed to absorb flight delays.

A. Airspace Concept Evaluation System

ACES is a gate-to-gate computer simulation of air traffic at airport, regional, and national levels, developed at the NASA Ames Research Center.[9] ACES simulates flight trajectories using aircraft models obtained from the Base of Aircraft Data[10] (BADA) and traffic data consisting of departure times and flight plans obtained from Airline Situation Display to Industry (ASDI) files. Traffic flow management and air traffic control models in ACES use airport and sector capacity thresholds for simulating delaying flights on the ground and in flight. ACES can also be run without traffic flow management, which enables simulation of traffic without capacity constraints as is done in this study. Typical ACES outputs include system performance metrics of arrival, departure, en-route, and total delays. Validation studies in Refs. 11 and 12 have shown that ACES generates delays and metrics comparable to those observed in the real-world.

In this study, ACES will be used for simulating traffic without airport and airspace capacity constraints. The resulting output data will be then used for generating inputs for the arrival scheduler, which is discussed in the next section.

B. First-Come First-Served Scheduler

The arrival scheduler uses the first-come first-served principle to create an arrival schedule for all flights. Inputs to the scheduler are the flight-plan departure times, sector entry and exit times, sector capacities, arrival times at the destination airport, and airport capacities. Flight plan departure times are derived from recorded ASDI flight schedule data for that day. Sector entry and exit times and arrival time at the destination airport are output by ACES simulation of unconstrained traffic. Sector capacities were considered unconstrained in this study. Airport arrival and departure capacities are typically obtained from the Aviation System Performance Metrics (ASPM) database.

The FCFS algorithm sorts all flights according to their departure times and then begins scheduling by allocating airport and sector resources to the flights. As flights occupy these resources for the time periods based on their transit-time, the available capacity is reduced to the point that none is available. Flights slated for later departure are delayed to find time intervals when airport capacity is available. The FCFS algorithm used here is an extension of the methods described in Refs. 13 and 14, and it is written in the Java programming language.

C. Delay Absorption Procedure

ACES's trajectory synthesizer module accepts a single speed as user-input for aircraft's cruise phase. This study, however, examines situations where aircraft fly at a reduced speed for part of their cruise phase in order to absorb delay. For that, a flexible trajectory synthesizer is needed, which can model cruise and descent trajectories when metering is implemented and aircraft fly at reduced speeds. This section summarizes the trajectory computation procedure employed in this study; a detailed description of it can be found in Ref. 15.

In the absence of wind, the magnitude of the airmass-relative acceleration resulting from thrust, drag, lift and gravitational forces on the aircraft modeled as a point mass is:

$$\dot{V} = \frac{T - D}{m} - g \sin\gamma \tag{1}$$

where V is airmass-relative speed (true airspeed), T is thrust, D is drag, m is mass, g is acceleration due to gravity and γ is the flight path angle. The altitude rate is:

$$\dot{h} = V \sin\gamma \tag{2}$$

The descent trajectory is divided into a series of flight segments to be consistent with current piloting and air traffic control procedures. Each segment of the trajectory shown in Fig. 1 is defined by setting constant two out of the following three control variables: thrust, speed, and vertical rate.[16]

Idle-thrust descent at constant Mach or calibrated airspeed (CAS) is the most frequently employed procedure by jet-engine aircraft. Pilots set the throttle to idle and maintain a constant Mach until a desired CAS is captured. Beyond that point, descent is maintained at constant CAS. For the constant Mach segment, flight path angle is obtained as:

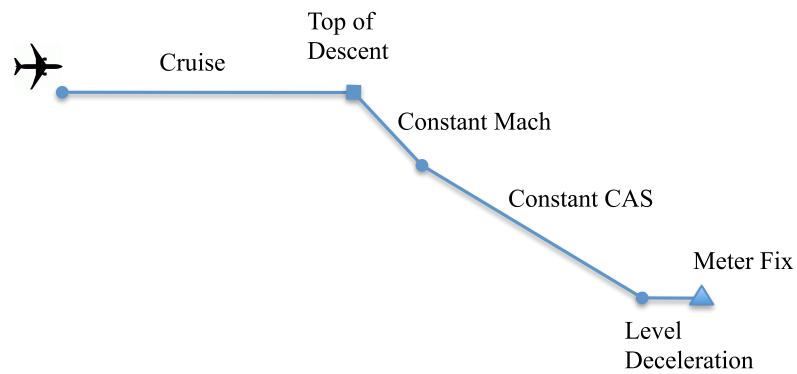

Figure 1. Vertical profile of aircraft's descent to the meter fix.

$$\gamma = \sin^{-1}\left\{\frac{T-D}{m}\cdot\left(M^2 a\frac{da}{dh}+g\right)^{-1}\right\} \tag{3}$$

where a is the speed of sound in air. For the constant CAS segment, flight path angle is:

$$\gamma = \sin^{-1}\left\{\frac{T-D}{m}\cdot\left(V\frac{dV}{dh}+g\right)^{-1}\right\} \tag{4}$$

Drag and thrust models were obtained from BADA version 3.9, and the Standard Atmosphere model was assumed for atmospheric conditions. Finally, the trajectory computation process was programmed in the MatLab/Simulink software environment.

III. Methodology

A. The OPSNET and ASPM Databases

To keep track of the operational efficiency of the air traffic system, the FAA and the Bureau of Transportation Statistics (BTS) keep records of a multitude of metrics including delay, number of operations, conditions at airports, and traffic management initiatives in databases. Several of the frequently used databases are: Aviation System Performance Metrics (ASPM), Air Traffic Control System Command Center (ATCSCC) Logs, BTS data, Enhanced Traffic Management System (ETMS) and OPSNET. Detailed descriptions of the contents of these databases are available in Ref. 17.

As discussed in the next subsection, selection of reference days for analysis in this paper is based on OPSNET data, which are available via https://aspm.faa.gov/opsnet. OPSNET data only include delays of fifteen minutes or more experienced by Instrument Flight Rule (IFR) flights that are reported by the FAA facilities. These data do not include delays caused by mechanical or other aircraft operator problems. Speed reductions and pilot initiated deviations around weather are also not reported. Taxi times spent under non-FAA facilities, for example under company/airport ramp towers, are not included in delay reports.[18]

Airport Acceptance Rates (AAR) and Airport Departure Rates (ADR), used as input for airport capacities in the FCFS scheduler, are obtained from the ASPM database, available via https://aspm.faa.gov/. ASPM provides information on individual flight performance and information on airport efficiency for every major US airport for every day since January 1, 2000. ASPM also provides quarter-hour AAR values, as well as delay data that are computed based on the Out-Off-On-In (OOOI) data provided by nine commercial and cargo carriers. Moreover, ASPM contains information on operated flights only, which means that canceled flights are not included in ASPM.

B. Selection of Reference Days

Capacity related delays and hence the distance required for extended metering varies across days of operations in the NAS with distinct air traffic characteristics. For example, metering requirements will be low on a day with an average number of scheduled flights and good weather conditions; extended metering may be required for the majority of flights on a day with an increased number of scheduled arrivals and adverse weather conditions. Therefore, analysis considers a set of days that are representative of all days of operations in the NAS with regards to demand for landings and delay.

Following the K-Means algorithm described in Ref. 19, all days from 2011 were organized into groups based on traffic volume and total delay on each day, using data obtained from OPSNET. Three levels of traffic volume – low, medium, and high – were considered, as well as three levels of delay. Table 1 displays the identification number (ID) assigned to each group of days. Out of nine possible combinations of traffic volume and delay, seven groups were generated. For two combinations, low-volume/high-delay and medium-volume/low-delay, no days were found with such traffic volume and delay characteristics in the NAS. Properties of the seven groups are summarized in Table 2. Group IDs are given in the first column. The third column of the table shows the number of days in the group, while the fourth one shows the number of days as percentage of total days in a year. The fifth column provides the average daily number of flights for each group. Columns six and seven show the average delay and the standard deviation of the delay in minutes. The data in this table show that there are fewer days in groups associated with high delays. For example, group number four consists of only seven days and group number seven of only thirty. On the contrary, group number five consists of 125 days. Overall, the majority of days in the NAS can be characterized as days with high traffic and low delays.

Table 1. Identification number for each group of days

		Delay		
		Low	Medium	High
Volume	Low	1	2	-
	Medium	-	3	4
	High	5	6	7

Table 2. Summary of properties of the seven groups

Group ID	Group Description	Number of Days	Percent	Mean Flights	Mean Delay (min.)	St. Dev. Delay (min.)
1	Low Volume – Low Delay	52	14%	28,385	10,901	10,610
2	Low Volume – Medium Delay	68	19%	34,091	24,651	21,271
3	Medium Volume – Medium Delay	17	5%	35,413	70,334	17,936
4	Medium Volume – High Delay	7	2%	36,117	136,932	21,176
5	High Volume – Low Delay	125	34%	40,581	20,385	11,543
6	High Volume – Medium Delay	66	18%	40,886	74,267	18,035
7	High Volume – High Delay	30	8%	40,690	139,096	28,677

Next, five days were selected from each group resulting into a total of 35 days that were used in this study. Days were selected such that different periods of the year are represented. Table 3 contains information on traffic volume and total amount of delay for each of these days. Data for the fourth and fifth columns, total number of flights and total delay respectively, were queried from OPSNET.

Table 3. Traffic volume and total flight delay for each analysis day

Group ID	Day of Week	Date	Number of Departures	Total Delay (min.)	Capacity-impacted Airports
				Low Volume, Low Delay	
1	Sunday	01/09/2011	30,705	16,669	BOS, LAX
	Wednesday	02/02/2011	27,932	9,189	BOS, EWR, LGA, PHL
	Saturday	03/12/2011	31,516	2,419	LAX, MSP
	Saturday	07/02/2011	31,283	5,897	LGA, BOS
	Saturday	10/15/2011	28,546	2,464	BOS, PHL
				Low Volume, Medium Delay	
2	Monday	01/03/2011	37,152	10,271	BOS, LAX, LAS
	Sunday	04/24/2011	32,445	44,734	IAD, LAX, BOS, SFO, DEN, DFW
	Saturday	08/06/2011	31,886	33,853	BOS, IAD, PHL, LAX, SFO
	Saturday	08/13/2011	31,589	63,038	LAX, ORD, IAD, JFK, PHL, CLT, DCA, DFW
	Sunday	11/20/2011	32,516	32,899	JFK, BOS, SFO, MIA, LAX
				Medium Volume, Medium Delay	
3	Monday	01/17/2011	35,159	86,897	ORD, BOS, MIA, PHL, SLC, MDW, MSP, SEA
	Monday	02/14/2011	36,609	57,883	IAD, SFO, PHL, LAX
	Sunday	06/12/2011	35,724	92,429	BOS, PHL, SFO, JFK, IAD, LAX, CLT
	Sunday	09/18/2011	34,669	62,557	ORD, BOS, PHL, LAX
	Monday	12/05/2011	36,488	67,565	PHL, SFO, BOS,DTW, CLE
				Medium Volume, High Delay	
4	Tuesday	01/18/2011	36,543	140,111	JFK, BOS, ATL, IAD, PHL, LGA, ORD, SFO
	Monday	02/21/2011	36,686	115,350	LAS, BOS, JFK, ATL, IAD, PHL, LGA, ORD
	Sunday	08/14/2011	35,034	142,804	JFK, LGA, EWR, IAD, PHL, LAX, BOS, DCA, CLT, DFW
	Sunday	08/21/2011	34,204	148,049	BOS, SFO, LAX, PHL, DFW, CLT, JFK, IAD, DCA
	Tuesday	12/27/2011	35,687	111,213	JFK, ATL, BOS, IAD, PHL, ORD, MSP, CLE, DTW, DCA
				High Volume, Low Delay	
5	Friday	01/14/2011	40,558	11,065	BOS
	Tuesday	03/15/2011	40,277	23,731	LAS, ATL, IAD, PHL, SFO, LAX
	Wednesday	06/29/2011	43,703	20,639	JFK, BOS, LAX, CLT
	Wednesday	09/21/2011	40,077	15,512	ATL, IAD, PHL, LAX, CLT, DCA
	Tuesday	11/01/2011	38,593	12,735	LAX, PHL
				High Volume, Medium Delay	
6	Tuesday	03/22/2011	40,201	68,600	BOS, ORD, LAX, DFW
	Wednesday	05/04/2011	41,230	67,973	BOS, IAD, LAS, PHL, SFO
	Wednesday	07/13/2011	42,634	80,371	IAD, ATL, SFO, LAX, MIA, PHX, DEN, CLT, DFW
	Thursday	09/08/2011	41,194	75,399	BOS, IAD, JFK, PHL, DCA, CLT
	Wednesday	11/23/2011	40,982	71,421	BOS, IAD, PHL, SFO, ORD, DFW, CLT
				High Volume, High Delay	
7	Thursday	03/10/2011	41,629	123,937	BOS, ATL, IAD, PHL, LGA, SFO, DCA, CLT, DFW
	Wednesday	05/18/2011	41,262	146,029	BOS, EWR, LAS, IAD, PHL, ORD, LAX, SFO, DFW, CLT, DEN
	Thursday	06/09/2011	41,920	235,640	IAD, ATL, BOS, JFK, SFO, LAX, ORD, DFW, DEN, CLT
	Tuesday	08/09/2011	41,087	119,123	BOS, JFK, DCA, PHL, CLT, LAX, SFO, DFW, PHX
	Wednesday	09/07/2011	38,838	164,647	JFK, BOS, IAD, EWR, PHL, DCA, DEN, DFW, CLT

The sixth column in Table 3 aims to provide a snapshot of the airports that had high arrival delays during each particular day. Since OPSNET data only include delays of fifteen minutes or more, an alternative metric for airport arrival throughput was used. The metric indicates which airports experienced a significant capacity reduction on that particular day. To estimate that, the airport's hourly capacity was plotted against its nominal capacity for each day. For the airport's hourly capacity, the declared AAR - obtained from ASPM - was employed. Airport's nominal capacity was defined as airport's most frequent hourly AAR throughout 2011. As an example of a capacity impacted airport, Fig. 2 displays hourly AARs for Logan International Airport (BOS) for May 18, 2011, a day in the NAS characterized as high-volume and high-delay according to Table 3. It can be observed in Fig. 2 that reported BOS capacity remained at approximately 29 arrivals per hour throughout the day - a significant drop from the nominal rate of 53 arrivals per hour. In general, when an airport experienced a reduction in AAR more than 30% with regards to its nominal AAR, and for more than three consecutive hours, it was characterized as impacted. Though delay is not explicitly computed, this method provides a rough overview of the state of the NAS during each particular day.

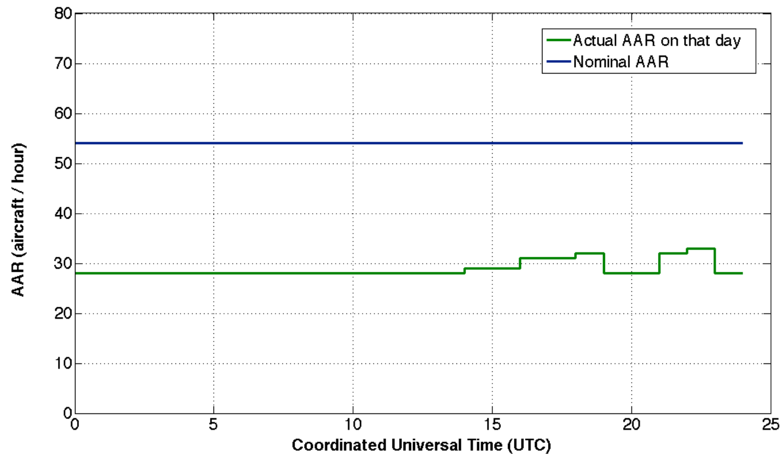

Figure 2. Hourly AAR and nominal AAR for BOS on 05/18/2011.

In this way, known delay patterns can be identified in Table 3. For each day listed in Table 3 that belongs to the convective weather season - June through August - east coast airports prevail as capacity-impacted airports. For example, on August 14, 2011 all major airports in the East Coast of the US experienced a significant capacity reduction: JFK, LGA, EWR, IAD, PHL, BOS, DCA, and CLT. Also, airports located in the northern part of the US prevail during winter days with medium or high delays. For instance, on January 17, 2011 the majority of impacted airports are located in northern US states: ORD, BOS, PHL, MDW, MSP, and SEA. It is expected that Centers handling traffic bound to these airports on these days will have to issue a large number of speed reduction advisories, if delay is to be absorbed through speed control.

C. ACES Unconstrained Simulation

The procedure for estimating the required metering distance and the Centers affected for each of 35 days is depicted in Fig. 3. It consists of three principal steps, which are described in the current and following subsections.

The first step consists of simulating air traffic without sector and airport capacity constraints using ACES with

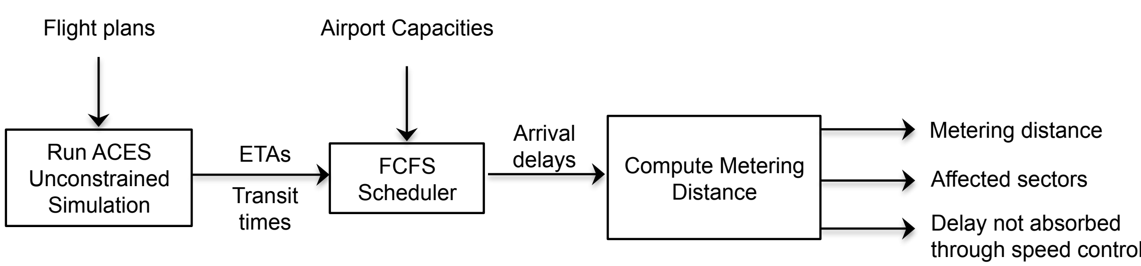

Figure 3. Experiment Procedure

the input flight plans. Flight plans contain the aircraft call-sign, aircraft type, departure airport, arrival airport, scheduled departure time, cruise speed, cruise altitude, and a sequence of waypoints that form the flight's route. Prior to ACES simulation, flight plans are read in from a recorded ASDI data file, parsed, and written out in a flight plan file. ACES output is post-processed to generate the sequence of sectors traversed by each flight, the sector transit times, and Estimated Time of Arrival (ETA) at the destination airport.

D. Generating Schedule of Arrivals

A series of Scheduled Times of Arrival (STAs) at the destination airport that meets the airport capacity constraints is created in the second step using the FCFS scheduler with the input ETAs, transit times, and sector sequence. For airport departure and arrival capacities, actual hourly departure and arrival rates are obtained from the ASPM database. Delay d is then defined for each flight as the difference between its STA and ETA at the destination airport. Forty busy US airports were selected for delay computation, which are displayed in Table 4. At these airports, time-based metering currently is or is planned to be implemented.

Table 4. List of airports considered in the analysis

ATL	DTW	LGA	PDX
BOS	EWR	MCO	PHL
BWI	FLL	MDW	PHX
CLE	HOU	MEM	SAN
CLT	HPN	MHT	SAT
CVG	IAD	MIA	SEA
DAL	IAH	MKE	SFO
DCA	JFK	MSP	SLC
DEN	LAS	OAK	STL
DFW	LAX	ORD	TEB

E. Computing Required Metering Distance to Absorb Delay

In the third step, the metering distance, s_m, required to absorb a given delay, d, through speed reduction is computed. The general case is illustrated in Fig. 4. It is important to note that the analysis focuses on the cruise and descent-to-meter-fix phases of the flight. Since reducing climbing speed results in higher fuel consumption, it was assumed that aircraft ascend at their nominal climb speeds until they reach the Top of Climb (ToC) point. Also, TRACON boundaries are modeled in ACES as a 40-nautical mile radius circle centered on the airport and flights proceed to the runway on a straight line and constant CAS once they enter the TRACON. Since no precise information on TRACON travel times was available in ACES, it was assumed that flights can absorb delays up to one minute inside the TRACON. The adjusted delay, therefore, that each flight must absorb before entering the TRACON – expressed in seconds – is:

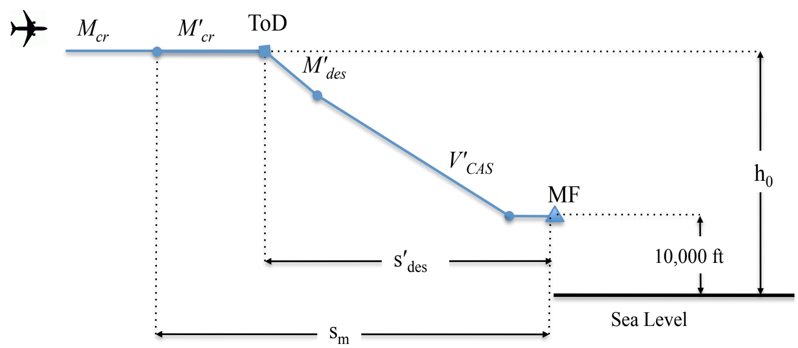

Figure 4. Vertical trajectory profile under metering.

$$d_{adj} = \max(0, d - 60) \tag{5}$$

To absorb d_{adj} the aircraft reduces first its nominal descent CAS up to 10% to V'_{CAS}. If V'_{CAS} is not sufficient to absorb delay d_{adj}, then the aircraft's nominal descent Mach speed is reduced up to 10% to M'_{des}. Note that for large jet transports it has been found that reducing descent CAS first results in lower fuel burn compared to reducing cruise Mach first.[15] If reducing descent CAS and Mach speed does not suffice for all delay d_{adj} to be absorbed, then the cruise Mach speed is reduced up to 10% to M'_{cr} at a distance s_m upstream of the meter fix. While other magnitudes for speed reduction can be applied too, for example 5%, reducing descent CAS or cruise Mach up to 10% offers two main advantages. First, it is a more drastic method to absorb delay compared to a reduction of lower magnitude. Second, it is the commonly expected range of speed reduction for Flight Deck Interval Management and Controller Managed Spacing lines of research.[20] As an example, a Boeing 737-800 has nominal cruise speed of 0.78 Mach. Reducing this speed by 10% results into Mach 0.70, which is the lowest speed usually assigned to large jet aircraft.

Yet, it was presumed that reduced speeds do not drop below certain thresholds. Minimum speed accepted, $V_{CAS,\min}$, is stipulated to be 30% above stall speed (see Ref. 10); it is a function of altitude, the aerodynamic configuration, and the weight of the aircraft. Therefore, the reduced CAS and Mach speeds are calculated through the following formulas:

$$V_{CAS}^{'} = \max\left(0.9V_{CAS,nom}, V_{CAS,\min}\right) \tag{6}$$

$$M_{cr}^{'} = \max\left(0.9M_{cr,nom}, M_{cr,\min}\right) \tag{7}$$

Next, let V_{cr} denote the true airspeed that is equivalent to M_{cr}, and let t_{des} and s_{des} denote the time and horizontal distance needed, respectively, to execute the descent to the meter fix. Also, let $V_{cr}^{'}$, $t_{des}^{'}$, and $s_{des}^{'}$ denote the previously defined variables under the reduced speed scenario. Then, the required metering distance, s_m, to absorb an amount of delay d_{adj} can be calculated through the following formula:

$$s_m = \left(\frac{s_{des}^{'} - s_{des}}{V_{cr}} + t_{des} - t_{des}^{'} + d_{adj}\right) \cdot \left(\frac{1}{V_{cr}^{'}} - \frac{1}{V_{cr}}\right)^{-1} + s_{des}^{'} \tag{8}$$

The total time and horizontal distance of the descent phase when no metering is present, t_{des} and s_{des}, can be obtained either through ACES simulation report data or through application of Eqs. (1) – (4). However, for cruise and descent at reduced speeds, $t_{des}^{'}$ and $s_{des}^{'}$ can only be calculated through Eqs. (1) – (4). In the situation when delay can be absorbed entirely in the descent phase, cruise speed is not reduced, and therefore $s_m = s_{des}^{'}$.

Finally, once the metering distance s_m is computed, the airspace sector where the aircraft must reduce its speed can be extracted. As mentioned before, speed control was not applied to the climb phase of the flight. Therefore, if s_m exceeds total flying distance from the ToC point to the meter fix, delay cannot be absorbed entirely through speed control. A certain portion of the delay will have to be taken on the ground, or absorbed airborne through either a path-stretch or holding pattern maneuver or more aggressive speed changes. These methods, however, are not the subject of this study, which focuses exclusively on speed reduction up to 10% of nominal speed.

IV. Results

This section highlights the main findings from the analysis of all 35 representative days of operations in the NAS. It is important to note that speed control was applied to a particular group of flights: jet aircraft whose ToC point is at least 250 nautical miles (nmi) from their destination airport. In this way, emphasis is given to flights that depart outside of an airport's TMA freeze horizon, which typically covers a range of approximately 250 nmi from the airport. This group of flights is hereafter referred to as *external jets*. Figure 5 provides an example of a flight from San Francisco (SFO) to Dallas/Fort Worth (DFW) that needs to absorb delay prior to landing. The green dot indicates the location where the aircraft, in one particular instance, should reduce its speed - by 10% - in order to absorb all of its arrival delay entirely through speed control. Thus, an air-traffic controller at Denver (ZDV) Center must issue a speed advisory to this flight. As it can be observed, the aircraft must reduce its speed three Centers upstream of its destination airport. Namely, these three Centers are ZDV, Albuquerque (ZAB), and Fort Worth (ZFW).

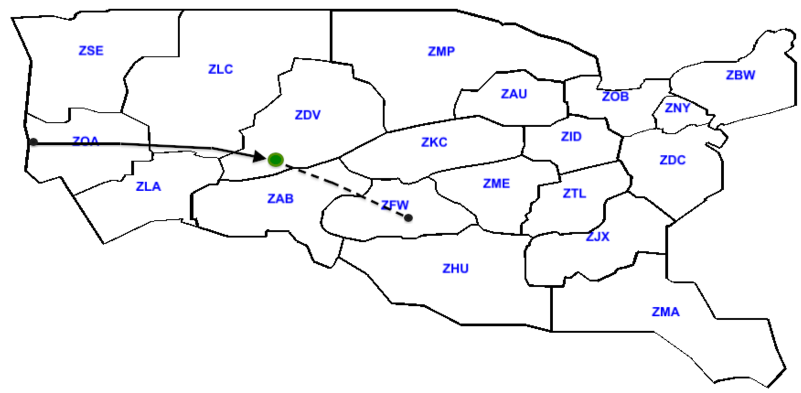

Figure 5. Example of flight bound to DFW reducing speed three Centers upstream of arrival airport to absorb delay.

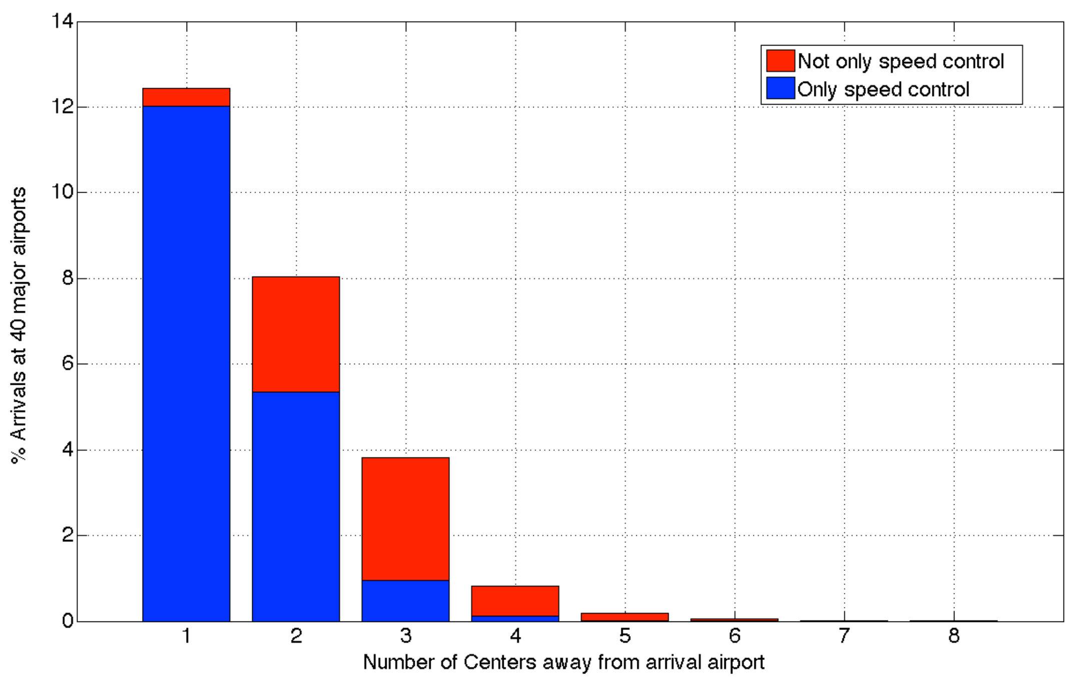

Figure 6. Relative frequency of number of Centers upstream of arrival airport where external jets should reduce speed – averaged across all days.

Figure 6 shows the number of delayed external jets as a function of the number of Centers upstream from destination airport where external jets had to reduce speed to absorb their arrival delay. The number of delayed external jets is displayed as a percentage of the total scheduled arrivals – delayed and undelayed – at the 40 analysis airports. The percentages are the weighted average across all 35 analysis days, weighted by the frequency of Volume/Delay groups as displayed in Table 2. Each bar in the plot is further divided into the percentage of external jets that were able to absorb all their delay through speed control and those that were not. As an example, 12.4% of scheduled arrivals were external jets and reduced speed inside the same Center where their destination airport was. Furthermore, 12% were able to absorb their delay only with speed control, whereas for the remaining 0.4% speed control was not sufficient.

The sum of all bar heights yields 25.4%, which is the percentage out of all flights that were external jets and were delayed more than one minute. The number of external jets that were able to absorb all their delay entirely through speed control account for 18.5% of all arrivals. This percentage taken in reference to 25.4% reveals that 73% of delayed external jets were able to absorb their arrival delay entirely through speed control. Furthermore, 68.4% of delayed external jets were able to absorb their arrival delay entirely through speed control in either the same or an adjacent Center from their arrival airport.

Focusing on this subset of flights that are external jets and can absorb all their arrival delay through speed control, 65% of them had to reduce speed inside the same Center where their destination airport was. Moreover, 93.5% were able to absorb all their arrival delay by reducing speed either one or two Centers upstream from their destination airport. This result indicates that implementing extended metering with speed control farther than second-tier Centers from an arrival airport can provide benefit to only 6.5% of those flights that are capable of fully exploiting it.

Next, if a speed reduction advisory is issued by an air-traffic controller for every aircraft that must absorb delay, one can plot the number of advisories issued by each Center. In the example of Fig. 5, ZDV Center issues that advisory, since the aircraft must reduce its speed in ZDV airspace. Figure 7 displays the number of advisories for speed reduction issued by each Center, computed as a weighted average across all analysis days. The brackets on each bar indicate the standard deviation of the bar's height. It should be clarified that the number of advisories shown in Fig. 7 include advisories for speed reduction issued to aircraft that cannot absorb all their arrival delay only by speed control. Assigning a red color to Centers that issued more than 400 advisories, orange to Centers that issued between 400 and 300 advisories, yellow to Centers that issued between 300 and 200 advisories, and green to Centers that issued less than 200 advisories, a corresponding heatmap can be created; see Fig. 8.

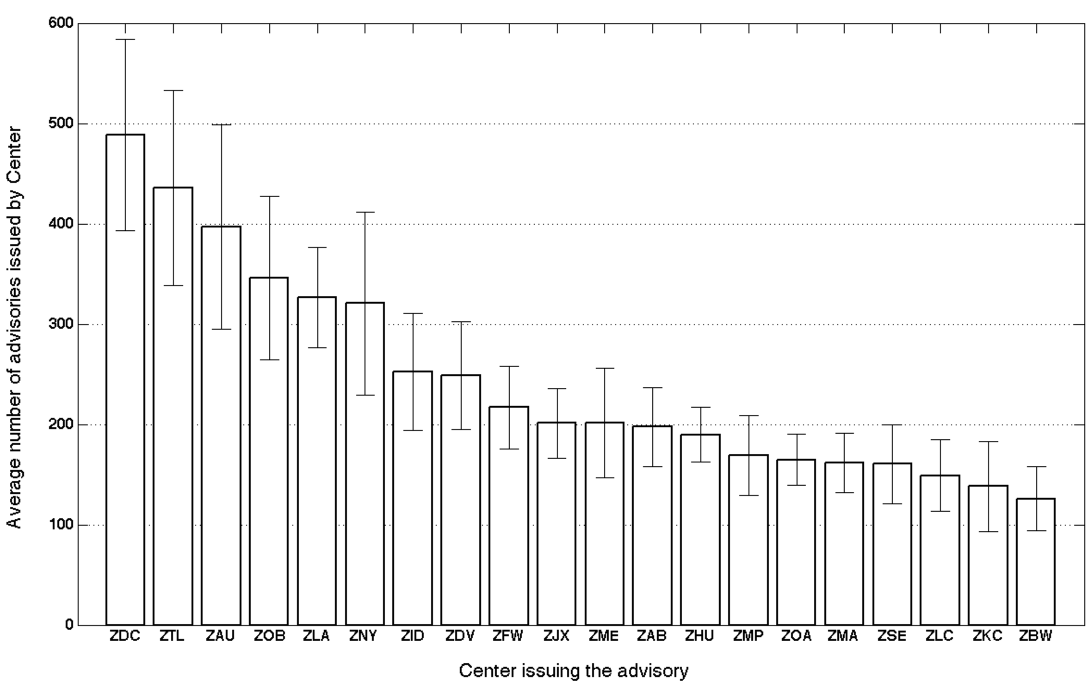

Figure 7. Number of speed advisories issued to external jets by each ARTCC – averaged across all days.

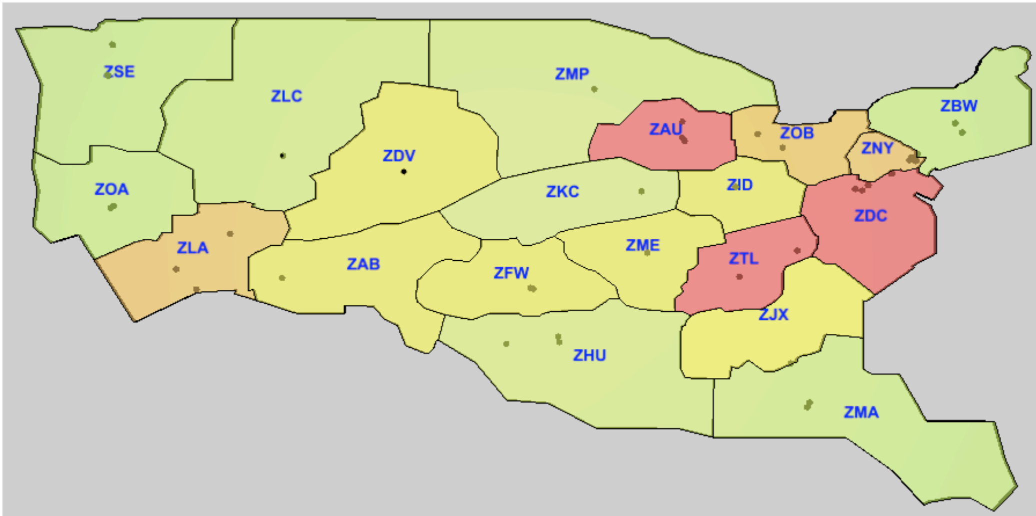

Figure 8. Map of ARTCCs with colors indicating the number of speed reduction advisories issued to external jets by each Center – averaged across all days. (red: >400 advisories, orange: between 400 and 300, yellow: between 300 and 200, green: less than 200)

Considering the top three Centers, namely ZDC, ZTL, and ZAU, metering patterns differ between these Centers. Out of all speed advisories issued by ZTL Center, 51% were to aircraft bound to an airport located in this Center, either Atlanta (ATL) or Charlotte (CLT). Similarly, out of all speed advisories issued by ZAU Center, 58% were to aircraft bound to an airport located inside the Chicago Center, either O'Hare (ORD), Midway (MDW), or Milwaukee (MKE). Only 32% of speed advisories issued by ZDC Center were to aircraft arriving at one of Baltimore (BWI), Reagan (DCA), Dulles (IAD), and Philadelphia (PHL) airports that are located within ZDC Center. Speed reduction advisories issued by ZDC to aircraft bound to airports inside the ZNY Center was equally high, namely 32% of total, while 5% of advisories issued by ZDC were to aircraft bound to a Boston (ZBW) Center airport.

Interestingly, Centers that issued less than 200 advisories are mostly Centers that handle traffic through the United States borderline. Despite the presence of busy airports within those Centers, such as SFO airport in the ZOA Center, BOS in ZBW, or MIA in ZMA, the number of aircraft that reduced speed inside those Centers was low. Being near the boundary of the NAS, these Centers interact with fewer adjacent ARTCCs. Therefore, they are less involved with extended metering traffic management initiatives.

In addition to the results displayed in Fig.7, Fig. 9 shows the number of speed advisories issued to external jets by each Center normalized by the daily traffic of the Center issuing the advisory. In this way, the number of speed advisories that each Center needs to issue is displayed as a fraction of the total number of flights that each Center handles on a daily average. Thus, for example, while ZSE issues a small number of advisories compared to other Centers, as it can be observed in Fig. 7, this number is high relative to ZSE's daily traffic volume, as it can be seen in Fig. 9.

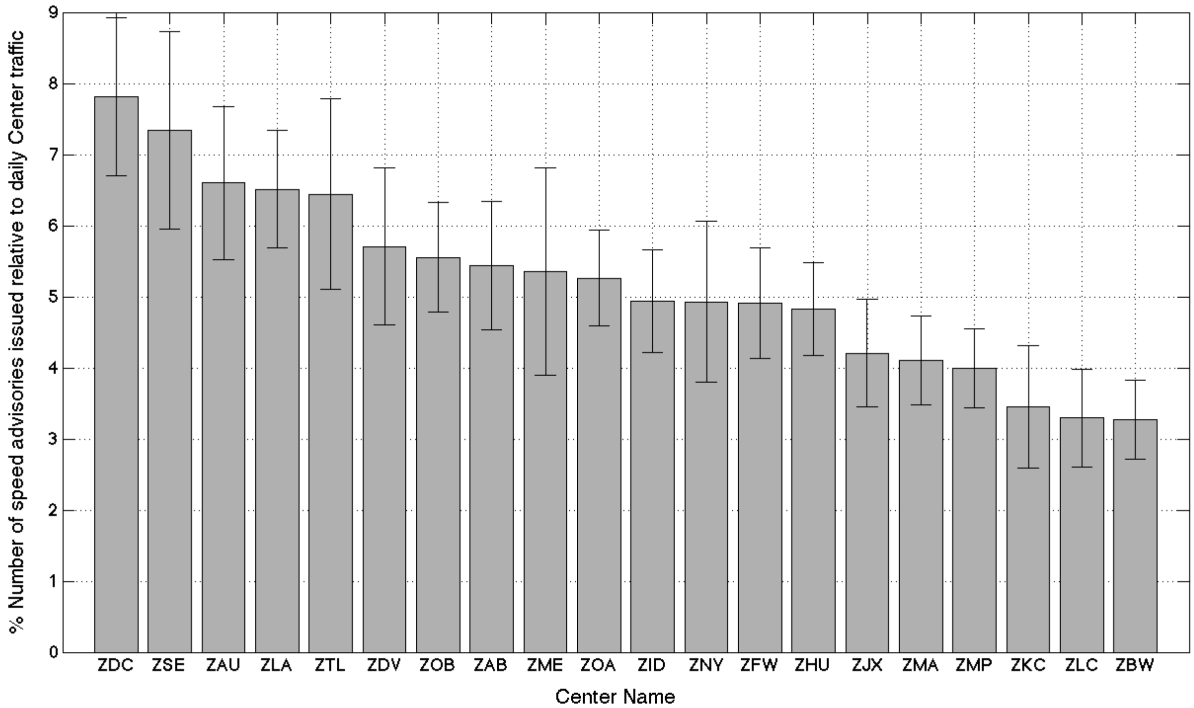

Figure 9. Number of speed advisories issued to external jets by each ARTCC realtive to ARTCC's daily number of flights – averaged across all days.

Analysis can be extended from a Center- to an airport-specific level. The objective in this case is to understand what percent of aircraft that are bound to a particular airport can absorb all their assigned delay entirely through speed control. As an example, for a flight departing from Boston and bound to New York available cruise and descent distance might not be sufficient to absorb its assigned delay merely by reducing speed. This aircraft will need, therefore, to either remain on the ground and depart later than planned or execute a path-stretch maneuver while airborne. Table 5 provides daily average statistics for external jets, which include number of scheduled arrivals, number of aircraft that absorbed all their assigned delay by speed control, as well as number of aircraft that could not absorb delay entirely by speed control, for each arrival airport considered in this study. For example, in ATL airport the weighted average - across the 35 analysis days - number of scheduled arrivals is 1235. For each of 35 days the percentage out of all scheduled arrivals at ATL that were external jets, and could absorb all their assigned delay entirely by reducing their cruise or descent speed was computed. These percentages were then averaged across all 35 days, and this was found to equal 18%. Similarly, the number of flights bound to ATL that could not absorb all delay merely by speed control was found to equal 8% of all scheduled arrivals, also averaged across all 35 analysis days. Furthermore, the ratio of 18% divided by 8% was computed 2.21. This ratio indicates the potential for absorbing delays through speed control; the higher the airport's ratio, the highest proportion of flights bound to this airport that can absorb all their delay through speed control.

Table 5. Statistics of traffic volume and delays averaged across all analysis days.

Arrival Airport	Number of Scheduled Arrivals	Absorb all delay by speed control	Cannot absorb all delay by speed control	Ratio	Arrival Airport	Number of Scheduled Arrivals	Absorb all delay by speed control	Cannot absorb all delay by speed control	Ratio
ATL	1235	18%	8%	2.21	LGA	496	15%	28%	0.53
BOS	465	17%	7%	2.52	MCO	424	24%	6%	4.08
BWI	346	19%	6%	3.36	MDW	316	25%	13%	2.01
CLE	251	15%	7%	1.98	MEM	474	16%	4%	4.62
CLT	699	14%	8%	1.77	MHT	70	19%	9%	2.25
CVG	232	14%	4%	3.29	MIA	520	16%	4%	4.35
DAL	200	7%	2%	4.40	MKE	207	21%	9%	2.38
DCA	388	18%	8%	2.18	MSP	584	22%	7%	3.22
DEN	852	23%	5%	4.54	OAK	217	15%	4%	4.02
DFW	874	22%	4%	5.69	ORD	1147	18%	9%	2.02
DTW	593	17%	7%	2.45	PDX	295	17%	3%	5.83
EWR	551	18%	13%	1.35	PHL	593	15%	10%	1.55
FLL	329	26%	9%	2.77	PHX	633	22%	3%	8.18
HOU	221	16%	4%	4.38	SAN	263	21%	7%	3.12
HPN	137	14%	4%	3.24	SAT	183	21%	3%	6.43
IAD	466	13%	5%	2.76	SEA	446	24%	3%	9.36
IAH	688	21%	5%	4.36	SFO	543	21%	12%	1.83
JFK	553	20%	9%	2.20	SLC	413	19%	3%	6.17
LAS	568	21%	3%	6.72	STL	257	19%	7%	2.88
LAX	797	19%	2%	10.29	TEB	169	9%	5%	1.68

Two airports with a high ratio are Phoenix (PHX) and Las Vegas (LAS), with the former exhibiting a ratio of 8.18 and the latter a ratio of 6.72. Stated differently, $21/(21+3)=87.5\%$ of all delayed external jets to LAS can absorb all their assigned delay through speed control, while this percentage rises to $22/(22+3)=88\%$ for the case of PHX. In actual practice, Adjacent Center Metering operations are supported at both PHX and LAS. Since these airports are also candidate locations for NASA's Air traffic management Technology Demonstration-1 (ATD-1) field test, they are examined in more detail.

As indicated in Table 5, external jets that are delayed more than one minute constitute 25% of all scheduled arrivals in PHX, averaged across all analysis days. The average delay per arrival for this group of flights was 204 seconds. A bar plot for number of Centers upstream of PHX where external jets must reduce speed is displayed in Fig. 10. It was calculated that 92% of all delayed external jets can absorb their delay in a first- or second-tier Center from PHX. With reference to those external jets that could absorb all their arrival delay through speed control, 74% had to reduce speed in ZAB's airspace, whereas 97.5% had to reduce speed either in ZAB airspace or in the airspace of a second-tier Center from PHX.

Figure 11 plots the number of speed advisories issued to external jets arriving to PHX by each Center, averaged across all 35 analysis days. The plot indicates that 109 advisories or approximately 75% of all speed advisories are issued in the ZAB Center. This finding can be explained if average delay per aircraft is considered in conjunction with PHX's geographic location. As mentioned in the previous paragraph, average delay per aircraft was 204 seconds for external jets. Absorbing that amount of delay through 10% speed reduction requires approximately 150 nmi.[15] As can be observed in Fig. 12, which depicts the results displayed in Fig. 11, the distance of PHX from other major airports as well as the large area covered by ZAB, provide ample space for absorbing delays on the order of three minutes partially or entirely by speed control.

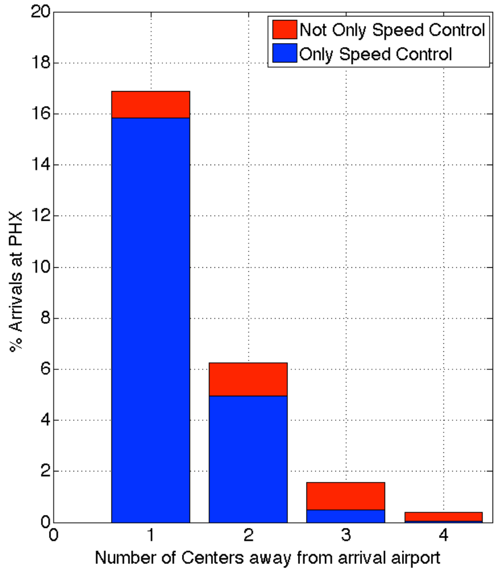

Figure 10. Number of Centers upstream from PHX where external jet arrivals to PHX should reduce speed – averaged across all days.

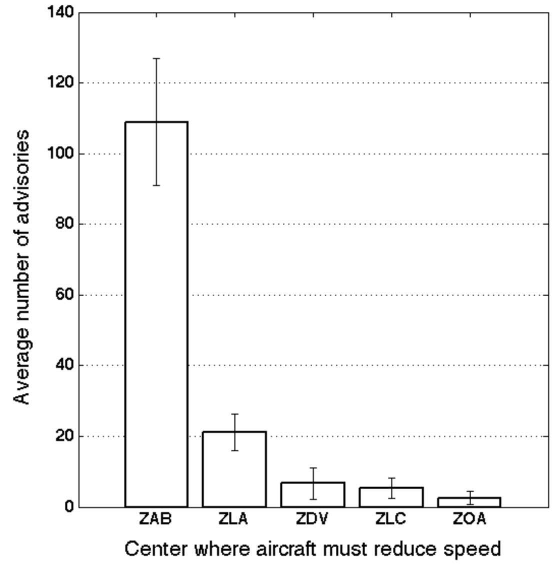

Figure 11. Number of speed advisories issued to external jets bound to PHX by each ARTCC – averaged across all days.

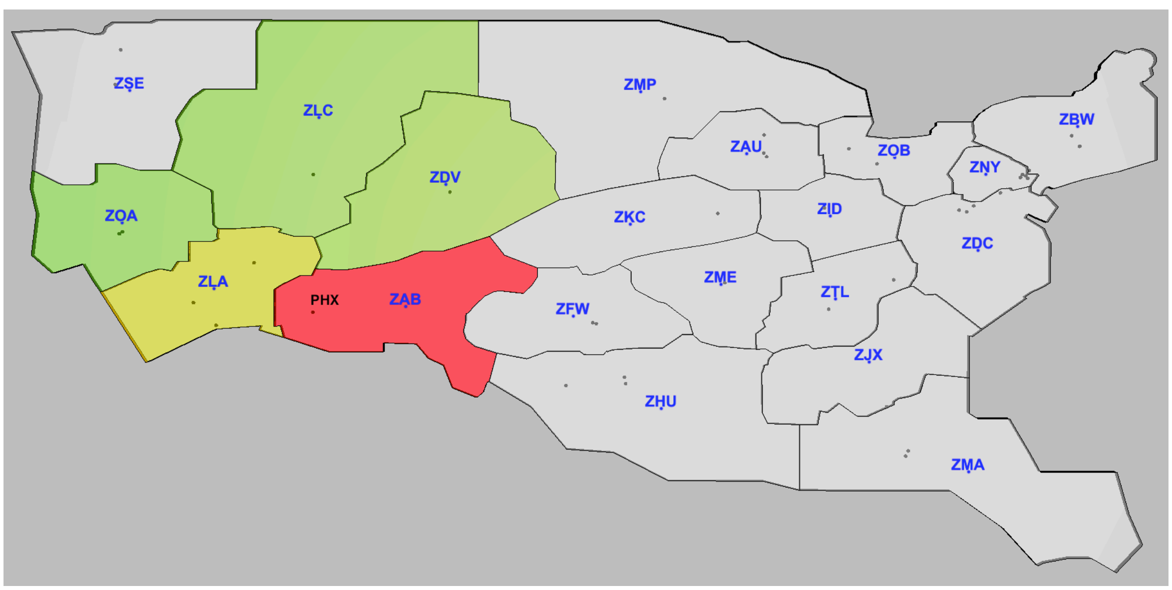

Figure 12. Map of ARTCCs with colors indicating the number of speed reduction advisories issued by each Center to external jets arriving at PHX – averaged across all days. (red: >60 advisories, yellow: between 15 and 30, green: less than 15)

Results do not change substantially for the case of LAS arrivals. Figure 13 provides the average percentages of external jets out of all arrivals at LAS that must reduce speed to absorb delay at a given number of Centers upstream from LAS. It was calculated that 88% of all delayed external jets can absorb their delay in a first- or second-tier Center from LAS. With reference to those external jets that could absorb all their arrival delay through speed control, 62% had to reduce speed in ZLA's airspace, whereas 91% had to reduce speed either in ZLA airspace or in the airspace of a second-tier Center from LAS.

Figure 14 plots the number of speed advisories issued to external jets arriving to LAS by each Center, averaged across all 35 analysis days. The plot indicates that 78 advisories or approximately 59% of all speed advisories are issued by the ZLA Center. This percentage of speed advisories issued by the first-tier Center is reduced compared to 75% for PHX, although average delay per external jet was 207 seconds – almost the same as in PHX. Careful comparison of Figs. 12 and 15 suggests that LAS resides closer to the boundaries with its neighboring Centers than PHX does, and therefore the required distance to absorb delay more frequently exceeds the distance to the ZLA Center boundary.

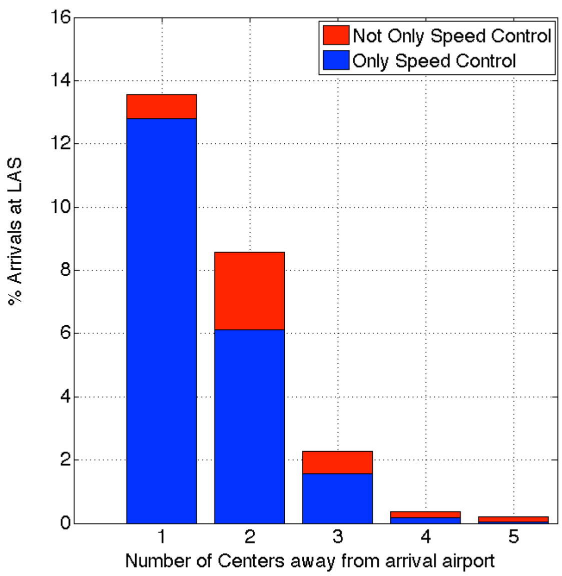

Figure 13. Number of Centers upstream of LAS where external jet arrivals to LAS should reduce speed – averaged across all days.

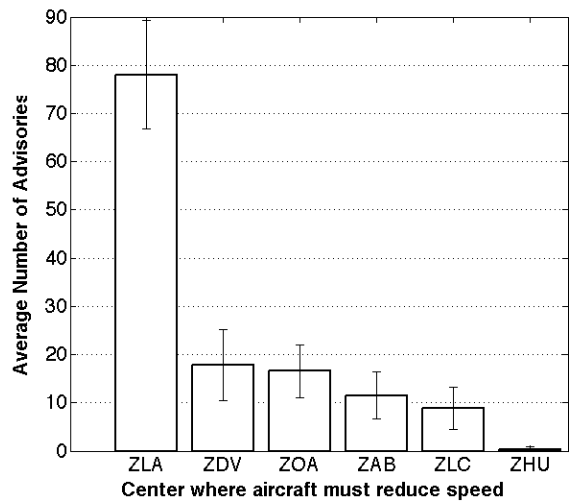

Figure 14. Number of speed advisories issued to external jets bound to LAS by each ARTCC – averaged across all days.

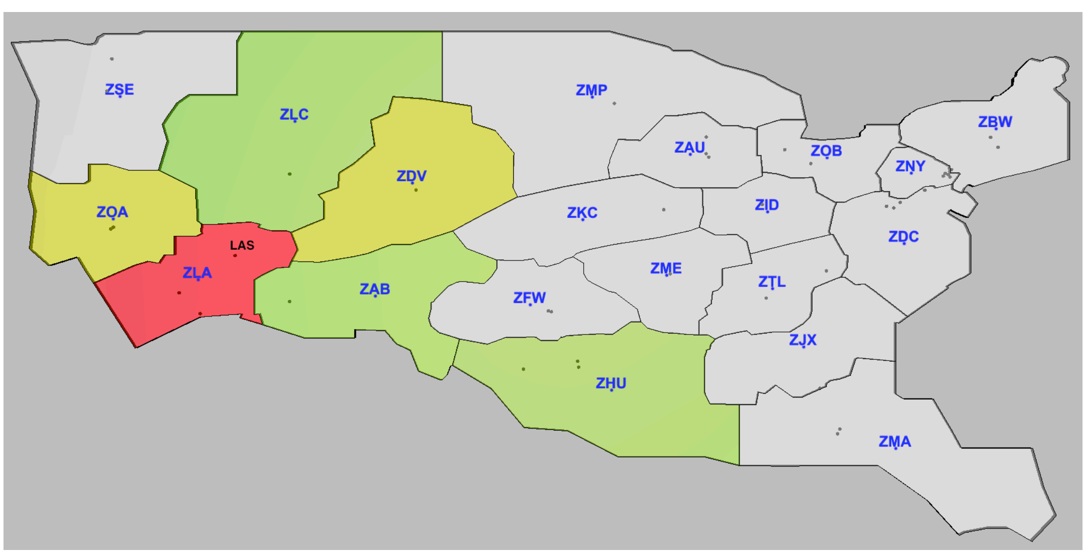

Figure 15. Map of ARTCCs with colors indicating the number of speed reduction advisories issued by each Center to external jets arriving at LAS – averaged across all days. (red: >60 advisories, yellow: between 15 and 30, green: less than 15)

V. Conclusions

This study analyzed the distance needed to absorb flight delays through reducing aircraft speed by 10%, when arrival metering is enforced at major US airports. Thirty five representative days of operations in the NAS with distinct traffic volume and delay characteristics were considered for the analysis. For each day, a simulation of the NAS traffic through ACES was conducted to generate delay-free aircraft landing times. Delays due to demand-capacity imbalance at the arrival airport were computed through a FCFS scheduler. Distances from the arrival airport where aircraft should reduce speed in order to absorb their assigned delay were calculated through an aircraft trajectory generator. Analysis then focused on jet aircraft reaching their top-of-climb point outside TMA's freeze horizon of their arrival airport.

Out of all aircraft assigned arrival delay, on average 73% were able to absorb that entirely through speed control. For the remaining 27%, cruising and descending at a reduced speed was not sufficient to absorb all the delay, and additional procedures such as path stretch or ground holding were needed. Also, a closer examination of the results showed that 68.4% of all aircraft assigned arrival delay were able to absorb that delay entirely through speed control in either the same or an adjacent Center from their arrival airport.

Focusing on those flights that were able to absorb their assigned delay entirely through speed control, 65% of them had to reduce speed inside the same Center where their arrival airport was. Moreover, 93.5% of those aircraft were able to absorb all their arrival delay by reducing speed when airborne in either the same or an adjacent Center from their arrival airport. This result indicates that implementing extended metering with speed control farther than second-tier Centers from an arrival airport will be used by only 6.5% of those flights that have the potential to absorb all their assigned delay through an up to 10% speed reduction.

Next, analysis focused on arrivals at PHX and LAS airports to support a major NASA project. Considering flights that could absorb their assigned delay entirely through speed control, the proportion achieving that in either the same or an adjacent Center from their arrival airport were 97.5% at PHX and 91% at LAS. Therefore, under today's levels of arrival demand at these airports, for those aircraft whose arrival delay is manageable through speed control only, a TMA Adjacent Center Metering program can handle the vast majority of them.

Finally, considering the number of advisories issued for speed reduction, the Centers that had to issue the largest on average number of advisories were Washington (ZDC), Atlanta (ZTL), Chicago (ZAU), Cleveland (ZOB), Los Angeles (ZLA), and New York (ZNY).

Acknowledgments

The authors wish to thank Charlene Cayabyab of UC Santa Cruz for her outstanding technical support on configuring and running the simulations, and for summarizing the output data. John Robinson of NASA Ames Research Center provided many helpful comments on this study.

References

[1]Swenson, H. N., Hoang T., Engelland S., Vincent D., Sanders T., Sanford B., and Heere K., "Design and Operational Evaluation of the Traffic Management Advisor at the Fort Worth Air Route Traffic Control Center," *1st USA/Europe Air Traffic Management Research and Development Seminar*, Online Proceedings, 1997.

[2]Capps, A. and Engelland, S., "Characterization of Tactical Departure Scheduling in the National Airspace System," *AIAA Aviation Technology, Integration and Operations Conference*, Online Proceedings, AIAA, Reston, VA, 2011.

[3]Federal Aviation Administration, "Concept of Operations for Time-Based Flow Management", Draft, Washington D.C., December 2009.

[4]Landry, S., Farley, T., Foster, J., Green, S., Hoang, T., and Wong, G. L., "Distributed Scheduling Architecture for Multi-Center Time-Based Metering," *AIAA Aircraft Technology, Integration and Operations Conference*, Online Proceedings, AIAA, Reston, VA, 2003.

[5]Landry, S. J., Farley, T., and Hoang, T., "Expanding the Use of Time-Based Metering: Multi-Center Traffic Management Advisor," *6th USA/Europe Air Traffic Management Research and Development Seminar*, Online Proceedings, 2005.

[6]Moertl, M., and Pollack, M., "Airline Based En Route Sequencing and Spacing Field Test Results," *9th USA/Europe Air Traffic Management Research and Development Seminar*, Online Proceedings, 1997.

[7]Delgado, L., Prats, X., and Sridhar, B., "Cruise Speed Reduction for Ground Delay Programs - Case of Study at San Francisco International Airport," working paper, 2012.

[8]Baxley, B. T., Johnson, W. C., Swenson, H. N., Robinson, J. E., Prevot, T., Callantine, T. J., Scardina, J., and Greene, M., "Air Traffic Management Technology Demonstration-1 Concept of Operations (ATD-1 ConOps)", NASA TM-217585, 2012.

[9]Meyn, L., Windhorst, R., Roth, K., Drei, D. V., Kubat, G., Manikonda, V., Roney, S., Hunter, G., Huang, A., and Couluris, G., "Build 4 of the Airspace Concept Evaluation System," *AIAA Modeling and Simulation Technologies Conference and Exhibit*, Online Proceedings, AIAA, Reston, VA, 2006.

[10]"User Manual for the Base of Aircraft Data (BADA) Revision 3.9," Eec note no. 11/08, Eurocontrol Experimental Centre, November 2008.

[11]Zelinski, S. J., "Validating the Airspace Concept Evaluation System Using Real World Data," *AIAA Modeling and Simulation Technologies Conference and Exhibit*, Online Proceedings, AIAA, Reston, VA, 2005.

[12]Zelinski, S. J. and Meyn, L., "Validating the Airspace Concept Evaluation System for Different Weather Days," *AIAA Modeling and Simulation Technologies Conference and Exhibit*, Online Proceedings, AIAA, Reston, VA, 2006.

[13]Palopo, K., Chatterji, G., and Lee, H.-T., "Interaction of Airspace Partitions and Traffic Flow Management Delay," *AIAA Aviation Technology, Integration and Operations Conference*, Online Proceedings, AIAA, Reston, VA, 2010.

[14]Meyn, L., "A Closed-Form Solution to Multi-Point Scheduling Problems," *AIAA Modeling and Simulation Technologies Conference*, Online Proceedings, AIAA, Reston, VA, 2010.

[15]Nikoleris, T., Chatterji, G., and Coppenbarger, R., "Comparison of Fuel Consumption of Alternative Descent Trajectories under Arrival Metering", *AIAA Guidance, Navigation, and Control Conference and Exhibit*, Online Proceedings, AIAA, Reston, VA, 2012.

[16]Zhao, Y, and Slattery, R. A., "Capture conditions for merging trajectory segments to model realistic aircraft descents", *Journal of Guidance, Control, and Dynamics*, Vol. 19, No.2, 1996.

[17]Krozel, J., Hoffman, B., Penny, S., and Butler, T., "Aggregate Statistics of the National Airspace System," AIAA-2003-5710, Proceedings of AIAA Guidance, Navigation, and Control Conference, Austin, TX, August 11-14, 2003.

[18]Federal Aviation Administration, "Order 7210.55F: Operational Data Reporting Requirements," U.S. Department of Transportation, October 1, 2009.

[19]Chatterji, G. B., and Musaffar, B., "Characterization of Days Based on Analysis of National Airspace System Performance Metrics," *AIAA Guidance, Navigation and Control Conference and Exhibit*, Online Proceedings, AIAA, Reston, VA, 2007.

[20]Prinzel, L. J., Shelton, K. J., Kramer L. J., Arthur, J. J., Bailey, R. E., Norman, R. M., Ellis K., and Barmore, B. E., "Flight Deck-Based Delegated Separation: Evaluation of an On-board Interval Management System with Synthetic and Enhanced Vision Technology," *IEEE 30th Digital Avionics Systems Conference (DASC)*, Online Proceedings, IEEE, Washington, DC, 2011.